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Perspective

# Choosing energy sources for battery-free pacemakers

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**THE BIGGER PICTURE** Battery-free pacemaker technology can eliminate the need for battery replacement surgeries of traditional pacemakers. Various energy harvesting and transmitting technologies can help realize this, such as utilizing energy from body movement, body heat, chemical energy in body fluids, and externally applied electromagnetic fields and ultrasound waves. However, these devices are not yet competitive with the mature technology of battery-operated pacemakers. Existing challenges include energy efficiency, biocompatibility, durability, and stability. Some of these technologies also provide opportunities for integrating additional functionalities, such as the real-time monitoring of biological signals. The development of battery-free pacemaker technology has potential to change implantable devices in general. Depending on the specific requirement and local operating environment of the implanted device, similar technologies can be developed based on the lessons learned here.

## SUMMARY

Battery-free cardiac pacemakers can overcome the limitations of traditional battery-dependent devices. This perspective discusses recent progress in developing energy-harvesting solutions for pacemakers, focusing on triboelectric, piezoelectric, thermoelectric, photovoltaic, biofuel cell, and wireless energy transfer mechanisms that harness biomechanical energy, body heat, ambient light, ultrasound, biochemical energy, and electromagnetic fields. These technologies eliminate the need for battery replacements, reducing surgical risks and enhancing patient comfort and quality of life. We also discuss future directions and challenges of these systems, such as energy conversion efficiency, biocompatibility, long-term reliability, safety and clinical concerns, and opportunities for additional functionalities, such as real-time feedback and control.

## INTRODUCTION

Cardiac pacemakers are essential in treating arrhythmias by maintaining proper heart rhythm through electrical stimulation.[1] They mimic natural cardiac pacing to ensure stable heart function, using components like microcontroller units, batteries, and output circuitry to sense and generate electrical impulses.[2] While effective, traditional pacemakers face challenges, particularly due to battery limitations that require replacement every 5–10 years, setting a clear benchmark for stability. Current self-powered prototypes have shown promising short-term performance in animal models, but their long-term stability remains to be fully validated. Accelerated aging tests, which simulate physiological conditions over extended periods, may offer insights into durability, though these methods must carefully replicate the complex and dynamic environment of the human body. Future research should focus on establishing protocols for stability testing and addressing the challenges of long-term implantation to ensure the reliability of battery-free pacemakers in clinical settings.

Recent reviews have highlighted the potential of battery-free technologies for pacemakers.[2,3] In this perspective, we will provide an overview of the technology with a focus on the existing challenges and speculative future research directions and perspective of system design, clinical deployment, and related regulatory and safety concerns.

Technologies such as piezoelectric, triboelectric, thermoelectric, photovoltaic, wireless radio frequency (RF), and biological fluid energy harvesting show promise for eliminating battery reliance, reducing surgical interventions, and improving patient quality of life.[4–7] Integrating these energy-harvesting methods into pacemakers could offer reliable, long-term solutions. Future pacemakers may also incorporate supplemental features, such as wireless communication and real-time monitoring. Balancing the energy demands of both fundamental and supplemental functions is a critical aspect in the development of next-generation battery-less pacemakers.

## DRIVING ENERGY SOURCES

The human body and surrounding environment provide diverse forms of energy that can be harnessed for powering pacemakers, such as biomechanical energy from body movements,[8–11] thermal gradients from body heat, electromagnetic waves, and biochemical energy from bodily fluids (Figure 2).[12,13] These energies are often characterized by their randomness, abundance, and widespread distribution. For instance, biomechanical energy from heartbeats and body movements is random but abundant, while thermal energy from body heat is consistent and available across the entire body surface. Radio frequency energy and ambient light are widely distributed but may fluctuate depending on environmental conditions (Figure 1A). The power levels of these energy sources vary significantly. Biomechanical energy can produce power on the scale of milliwatts, whereas thermal energy is typically in the range of tens to hundreds of microwatts. This section provides a detailed introduction to the principles and applications of various driving energy sources used for cardiac pacing. Table 1 summarizes their characteristics.

### Biomechanical energy

Utilizing intrinsic myocardial activity as a continuous energy source offers a promising solution for powering battery-free pacemakers.[14] Harvesting biomechanical energy to convert the mechanical forces of the heart into electrical energy is an effective approach. Materials such as lead (Pb) zirconate titanate (PZT), zinc oxide (ZnO), and certain piezoelectric polymers have the ability to generate electric charges when subjected to mechanical stress.[8,15] However, the long-term biocompatibility of PZT is a concern due to potential pharmacodynamics (Pd) toxicity, especially in implantable applications. Recent studies have explored Pb-free alternatives, such as potassium sodium niobate and barium titanate, which exhibit comparable piezoelectric performance with enhanced safety profiles.[16,17] In the context of cardiac pacemakers, piezoelectric nanogenerators (PENGs) convert mechanical energy from physiological movements (e.g., cardiac contractions or respiratory motions) into electrical energy through the deformation of piezoelectric materials (Figure 1B). These systems typically consist of piezoelectric materials, a flexible substrate, and an external load. For example, Li et al. developed an implantable piezoelectric energy generator (iPEG) designed to harvest mechanical energy from the heart. When tested in pigs, the iPEG generated a current of 15 $\mu$A, which was sufficient to power a commercial pacemaker chip (Figure 3B).[18] Xie et al. reported an epicardial pacing strategy using cystic piezoelectric elements, which enhanced kinetic energy collection during heart movement. After 12 weeks of implantation in rats, the average voltage was 2.1 mV, proving the feasibility of this approach for cardiac pacing (Figure 3C).[19]

Despite the progress, the biocompatibility of implanted piezoelectric energy-harvesting devices and their impact on cardiac function warrant careful consideration. Studies indicate that, although flexible piezoelectric vibration energy harvesters are not toxic to myocardial tissue, their implantation may still influence cardiac function to some extent. In a 12-week test of implanted piezoelectric devices in rats, cardiac ultrasound assessments revealed that heart rate and primary cardiac functional indicators, such as the left ventricular ejection fraction and left ventricular fractional shortening, in the experimental group remained stable compared to their baseline values, but the values were still lower than those in the control group. Additionally, biochemical analyses demonstrated differences in total bilirubin and triglyceride levels between the experimental and control groups, suggesting that the device may have certain physiological effects on the body. In practical applications, these potential risks and impacts should be thoroughly considered.[20] To ensure that no adverse effects occur in the human body, the selection of raw materials for device construction is crucial for achieving the necessary tissue compatibility as well as the overall electrochemical and electromechanical performance of the device.

Triboelectric nanogenerators (TENGs) and PENGs operate based on fundamentally different principles, which lead to distinct characteristics and applications. TENGs generate electricity through the triboelectric effect combined with electrostatic induction, typically driven by periodic contact-separation or sliding motions. In comparison, PENGs rely on the direct conversion of mechanical stress into electrical charge (Figure 1C). As a result, TENGs can achieve higher output voltages but with relatively lower currents compared to PENGs. Consequently, TENGs and PENGs are suited to different applications. PENGs are ideal for capturing energy from small-amplitude, periodic mechanical deformations, such as heartbeats or vascular pulsations, where high-frequency, low-magnitude forces are present, while TENGs excel in environments with larger, more frequent deformations, such as walking or breathing, where high-voltage output is needed to power devices under dynamic and varying mechanical conditions.[21–23] For example, Liu et al. reported a capsule-shaped self-powered intracardiac pacemaker (SICP) based on the coupling effect of triboelectric and electrostatic induction (Figures 4A and 4B).[24] The SICP integrates an energy-harvesting unit, a power management unit, and a pacemaker module within a miniaturized structure (Figure 4C). The device was implanted into a pig model, achieving an open-circuit voltage of 6.0 V and pacing for atrioventricular block model animals over 3 weeks (Figures 4D and 4E). In addition to the heart, kinetic energy from other organs and tissues—such as muscle stretching,[22] respiratory airflow,[25,26] and aortic contraction[27]—can also be harvested, offering diverse energy sources for the development of self-powered pacemakers.

Despite the promising application prospects of TENGs and PENGs, their biocompatibility and potential impact on cardiac function warrant careful consideration. Biochemical analyses indicated physiological effects, highlighting the need for careful material selection to ensure tissue compatibility and optimal electrochemical and electromechanical performance.[20] Similarly, TENGs present concerns due to their periodic contact and separation mechanism, which may cause chronic stimulation of cardiac tissues, leading to inflammation, fibrosis, and disruptions of myocardial function. Implantation may also affect cardiac hemodynamics, increasing the risk of thrombosis and arrhythmias.[28] While TENG materials generally exhibit good

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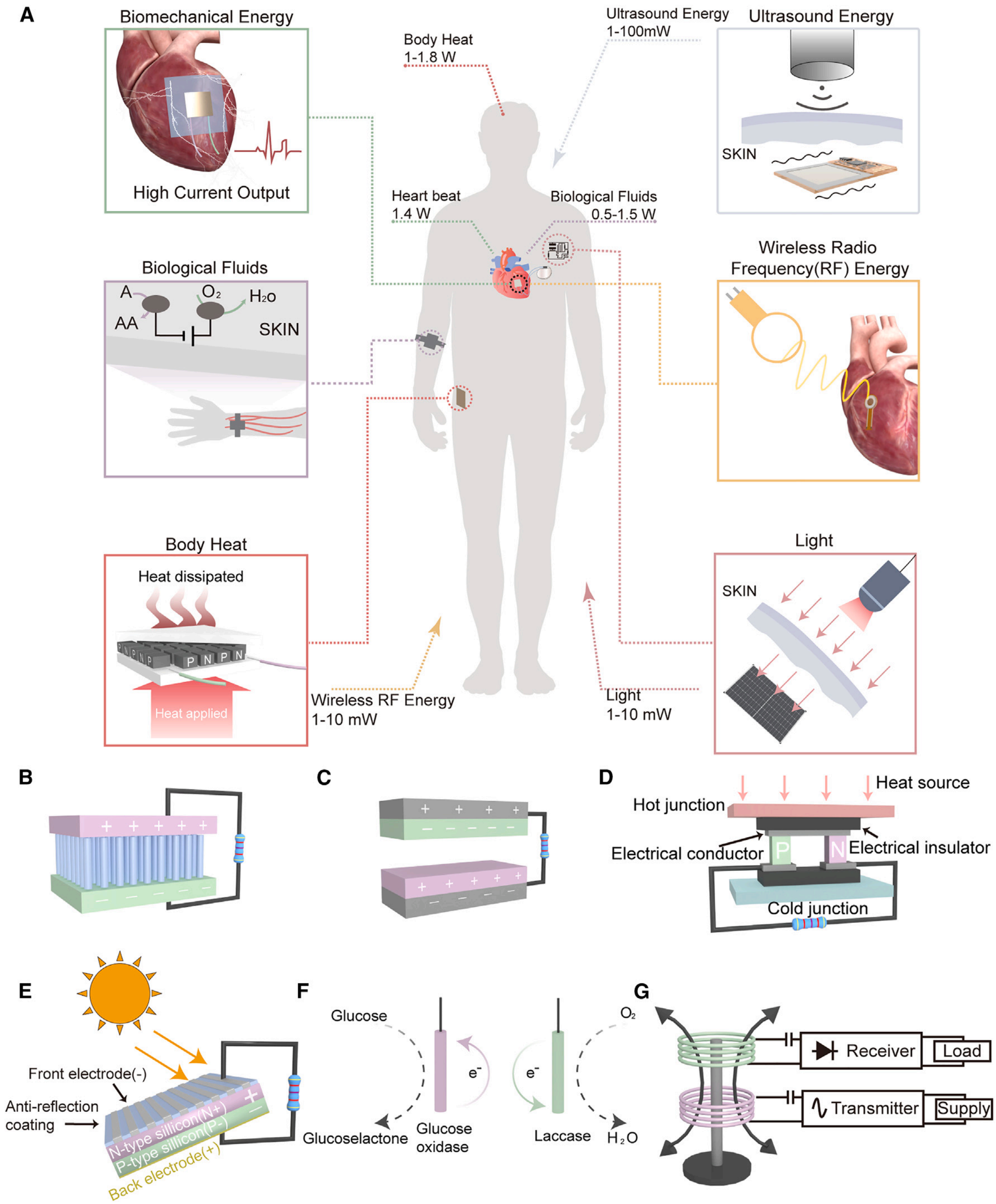


**Figure 1. Human energy conversion and utilization technology overview**

(A) Schematic of energy-harvesting technology for a battery-free pacemaker.[6,15,21,22] The power values listed in the figure are directly obtained from the collected literature or calculated using formulas. The following are the derived formulas: heart beat power formula: $P = P_{mean} \times CO$; $P_{mean} = 100\ mmHg, CO = 6.3\ L/min$.[21] Body heat power formula: $P_{heat} = BMR \times A \times f$; $BMR = 70\ W/m^2, A = 1.7\ m^2, f = 10\% \sim 15\%$.[22,70] Biological fluid power formula: $P = \Delta G \times \dot{n}$; $\Delta G \approx 450 kJ/mol$, $\dot{n} = 3.34 \times 10^{-7} mol/s$.[20,71,72]

(B) A schematic of a PENG.

(C) Classic types of TENGs: vertical contact-separation mode, lateral sliding mode, single-electrode mode, and freestanding mode.

(D) A schematic of a TEG.

(E) A schematic of solar cells.

(F) A schematic of BFCs.

(G) A schematic of wireless RF energy transmission devices.

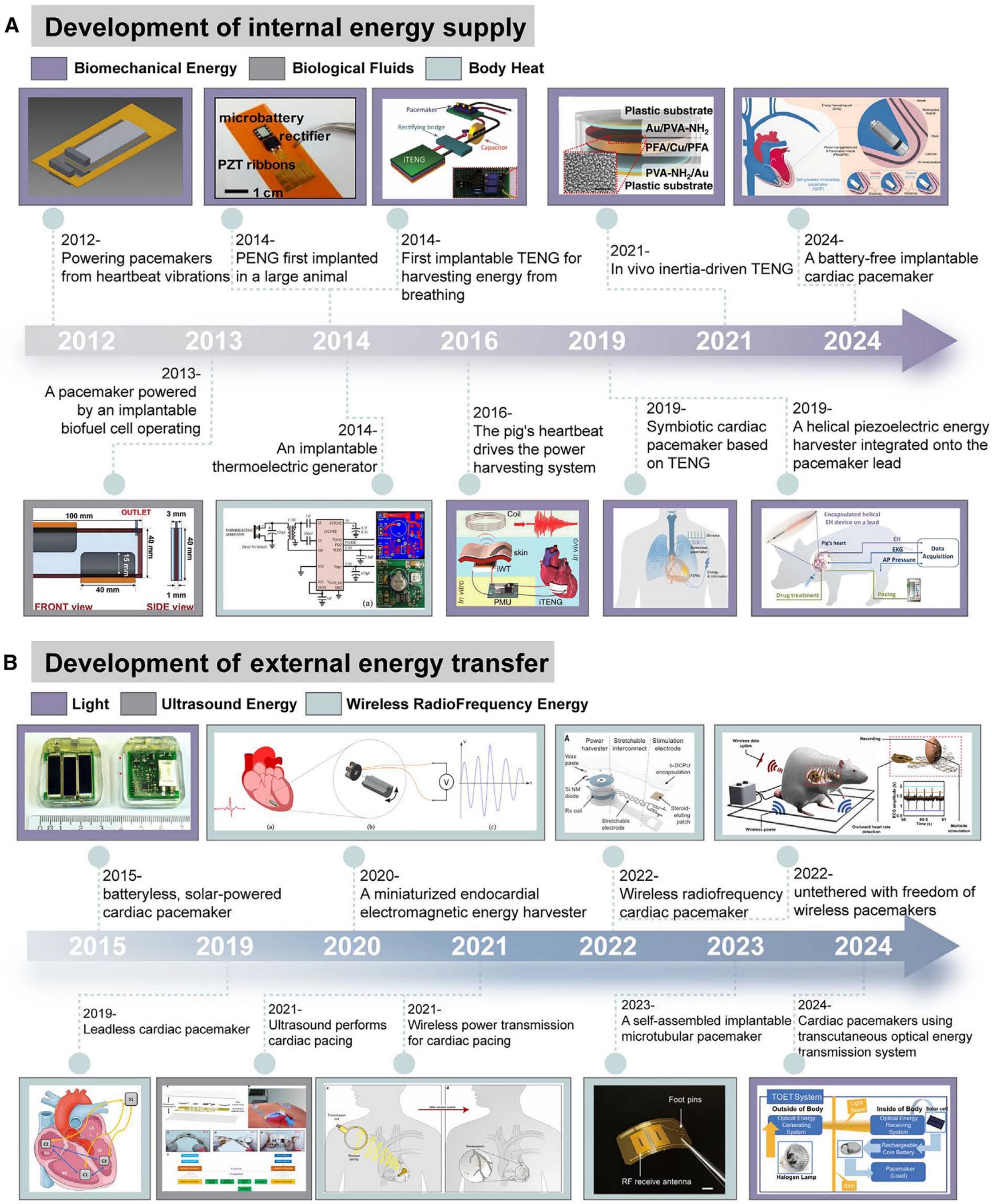


**Figure 2. Development of driving energy for cardiac pacemakers**

(A) Development of internal energy supply cardiac pacemakers.[24,33,37,56,61,65,73–76]

(B) Development of external energy transfer pacemaker.[12,14,40,42,50–52,59,77]

biocompatibility, their surface characteristics and chemical composition, along with implantation-related infection risks, could trigger immune responses or chronic inflammation. Furthermore, mechanical friction and the moist cardiac environment may accelerate material aging and wear, compromising long-term device stability and durability.[23,29]

## Body heat

The operation of thermally driven pacemakers is primarily based on thermoelectric conversion, which involves converting thermal energy stored within the body into electrical energy to power the pacemaker. Thermoelectric generators (TEGs) and pyroelectric nanogenerators (PyENGs) can achieve this goal based on

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**Table 1. Performance comparison of various energy conversion technologies**

| Types | Materials | Structures | Energy conversion efficiency | Power output (V) | *In vivo* experiments | Cost | Reference |
|---|---|---|---|---|---|---|---|
| PENG | PVDF/ZnO/rGO | nanofiber electrode | moderate | 6.06–20 | dog | high | Zheng et al.[37] |
| | PMN-PT | elastic skeleton with piezoelectric composites | | | pig | high | and Liu et al.[60] |
| TENG | polymer or metal | double contacting layers | low to moderate | 6–65.2 | pig/dog | low | Zhang et al.,[35] Moon et al.,[38] and Amin Karami et al.[61] |
| TEG | polymer or metal | layered design | low | 0.0199–2.5 | rabbit | low | Rao et al.[7] and Eppink et al.[62] |
| Light | polymer and silicon-based materials | layered photovoltaic module | moderate to high | 0.92–1.29 | pig/chicken | moderate | Xie et al.,[20] Huang et al.,[39] Zhao et al.,[63] Xu et al.,[64] and Azimi et al.[65] |
| RF | biodegradable materials | dual-coil wireless design | moderate | 1–30 | pig/rabbit | moderate | DeForge et al.[66] and Ryu et al.[67] |
| Biofuel | enzyme/metal electrode | fluidic BFC | moderate | 0.47–1.2 | none | moderate | MacVittie et al.[68] and Imani et al.[69] |

different operating principles. TEGs convert thermal energy into electrical power through the thermoelectric effect,[30–32] while PyENGs rely on the pyroelectric effect.[7,21] PyENGs require periodic temperature changes to generate electricity effectively, making it unsuitable for implantable applications, so we will focus on TEGs. When two different thermoelectric materials are connected and exposed to a temperature difference, charge carriers move from the hotter to the cooler end, creating an electric current. This process continues as long as the temperature gradient is maintained (Figure 1D).

In 2013, Yang et al. created a prototype of an implantable TEG featuring two implanted TEG modules along with a boost circuit that included an integrated direct current (DC)/DC converter to stabilize and increase the voltage output.[33] When implanted in rabbits, both single-stage and multi-stage TEG modules produced output voltages exceeding 20 mV, and the boost circuit consistently put out 3.3 V, sufficient to drive an LC oscillation circuit at 1-s pulse intervals. The power generated by this setup was greater than that required by conventional pacemakers. The temperature difference in the multi-stage TEG module remained stable at approximately 1.1°C, increasing the voltage of the TEG module while maintaining consistent output from the boost circuit and clock signal.

However, the application of TEGs in heart-related scenarios faces numerous unresolved challenges. As a complex physiological system, the human body experiences temperature fluctuations due to environmental changes, activity levels, and health conditions, which can disrupt the stable temperature difference required by TEGs. In addition to enhancing energy harvesting and storage technologies, minimizing the loss of available heat is crucial. Tupe et al. developed a TEG that demonstrated the feasibility of converting human body heat into electrical energy. They selected polydimethylsiloxane as the substrate due to its low thermal conductivity and incorporated a thermocouple structure with a silicon dioxide insulation layer to concentrate heat along the most efficient conversion path, thereby reducing energy dissipation to the surrounding environment.[34] The TEG, when attached to the human body, generated an output voltage of 5 mV, an output current of 10 μA, and an output power of 50 nW with a temperature difference of 7°C between the ambient and body temperature. This study highlighted that the performance of TEGs is linked to external irreversibility, implying that optimizing both external and internal factors is essential for maximizing the efficiency.

The operation of TEGs may also cause abnormal local tissue temperatures. Excessively high or low temperatures can trigger thermal stress responses in myocardial tissue, disrupting normal cellular metabolism and function. Moreover, TEGs often use heavy metal semiconductor materials, such as $Bi_2Te_3$, which pose biocompatibility risks in long-term use. In cases of inadequate encapsulation, toxic material leakage could harm surrounding cardiac tissues.[35,36] Optimizing thermal management design, incorporating temperature monitoring and feedback regulation functions, and selecting biocompatible materials can enhance the safety and reliability of TEGs in cardiac pacing devices. The device for collecting energy for TEGs (e.g., power management units, thermal interfaces, and encapsulation structures) is still in the stage of simulation and experimental verification, which provides a theoretical basis and technical support for the application of TEGs in cardiac pacemakers to a certain extent. As the technology continues to mature and improve, TEG-driven cardiac pacemakers are expected to undergo clinical trials.

## Light

Light-driven pacemakers operate by converting optical signals into biocurrents (i.e., electrical currents within biological systems) through a specialized porous material layer. This material enhances light absorption and charge separation, enabling efficient photoelectric conversion. The resulting biocurrents interact with cardiac cells, modulating their electrical activity to regulate the heartbeat. When photons strike a semiconductor material, they excite electrons, allowing them to move from the valence band to the conduction band. This generates an electrical potential difference, which drives electrons through an external circuit to produce an electric current. Photovoltaic energy conversion

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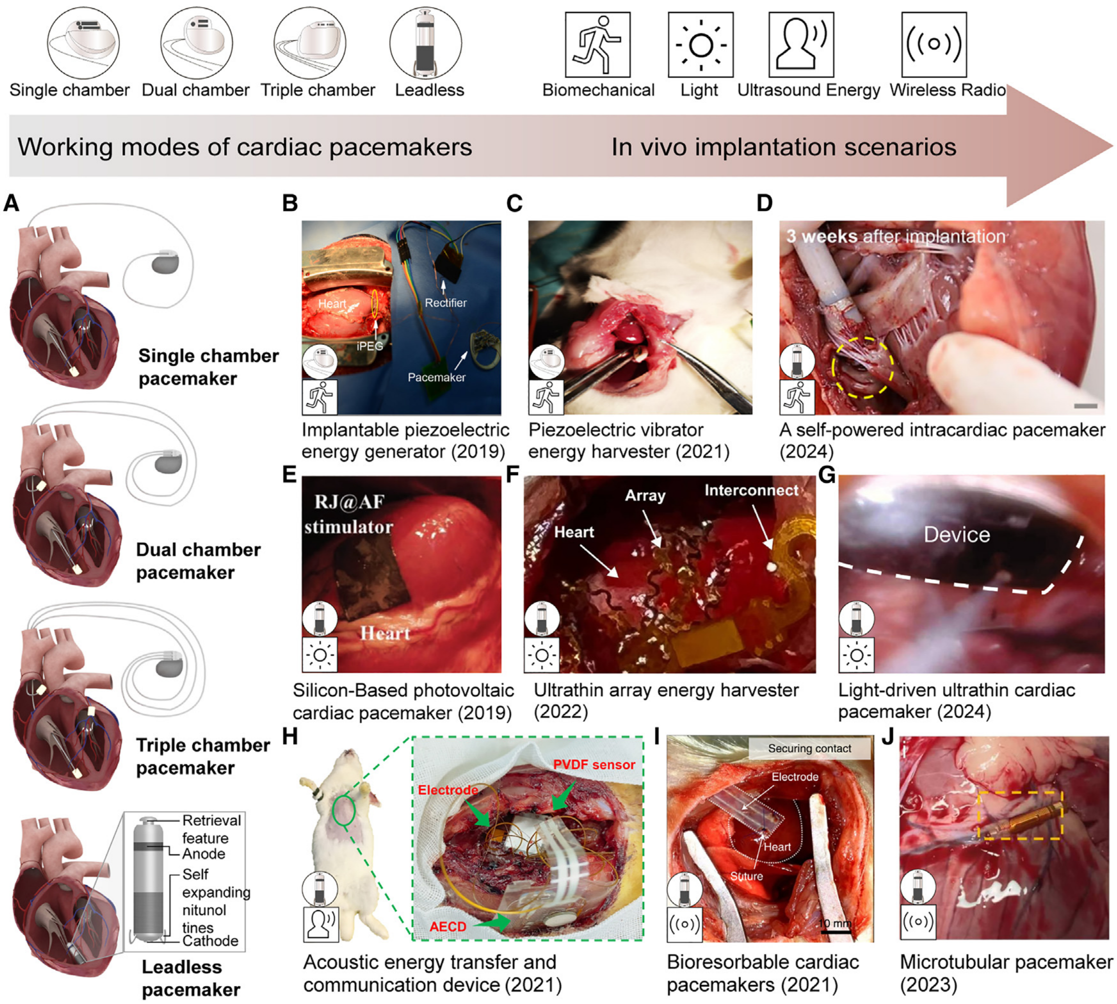


**Figure 3. Advances *in vivo* application of battery-free pacemaker devices**

(A) Diagram of pacemaker classification according to number of pacemaker leads and their internal lead distribution and stimulation points (left).

(B) Photograph of the implanted iPEG in parallel mode, which is connected to the pacemaker through a rectifier.[18]

(C) Implantation of the piezoelectric vibration energy harvester for self-powered cardiac pacemakers near the cardiac apex.[19]

(D) Photographs of an SICP fixed to the endocardium at 3 weeks (scale bar: 0.5 cm).[24]

(E) Battery-free, conformal contact, flexible silicon-based photovoltaic pacemaker using an a-Si:H RJ photostimulator manufactured on a flexible conductive aluminum foil (AF).[41]

(F) Images of subcutaneous implants in the chest and heart of a mouse. Through the machine learning-guided ultra-thin array design, the seamless integration of the biological interface and the heart is realized.[42]

(G) Photographs of endoscopic views during the minimally invasive pig heart pacing process.[43]

(H) A thin, battery-free, flexible, and implantable system based on flexible electronics technology is used to fix the position of each part of the device in cardiac pacing experiments.[50]

(I) Implantation and operation of a bioabsorbable leadless pacemaker in a chronic *in vivo* rat model.[12]

(J) Microtubule pacemakers were implanted in anterior cardiac veins (ACVs) of anesthetized pigs to restore heart conduction and myocardial contraction.[52]

has been explored as a method to power cardiac pacemakers using external light sources (Figure 1E).[37–39]

Haeberlin et al. designed a battery-free pacemaker powered by a solar module capable of converting transcutaneous light into electrical energy.[40] Infrared light, which can penetrate the skin, allows subcutaneous solar modules to harvest energy. *In vitro* tests showed that the average output power of the solar module was 1,963 μW/cm$^2$ in direct sunlight, 206 μW/cm$^2$ outdoors in the shade, and 4 μW/cm$^2$ indoors. *In vivo* tests demonstrated that a pacemaker equipped with an energy buffer, such as a rechargeable battery or supercapacitor, could continue pacing for 1.5 months in complete darkness after only a brief (e.g., 5–15 min) exposure to light.

Liu et al. developed a radial junction photoelectric pacemaker that was developed to address the challenges of maintaining stable energy acquisition under varying light conditions while optimizing material biodegradation to suit different treatment cycles.[41] *In vivo* experiments demonstrated that external photostimulation

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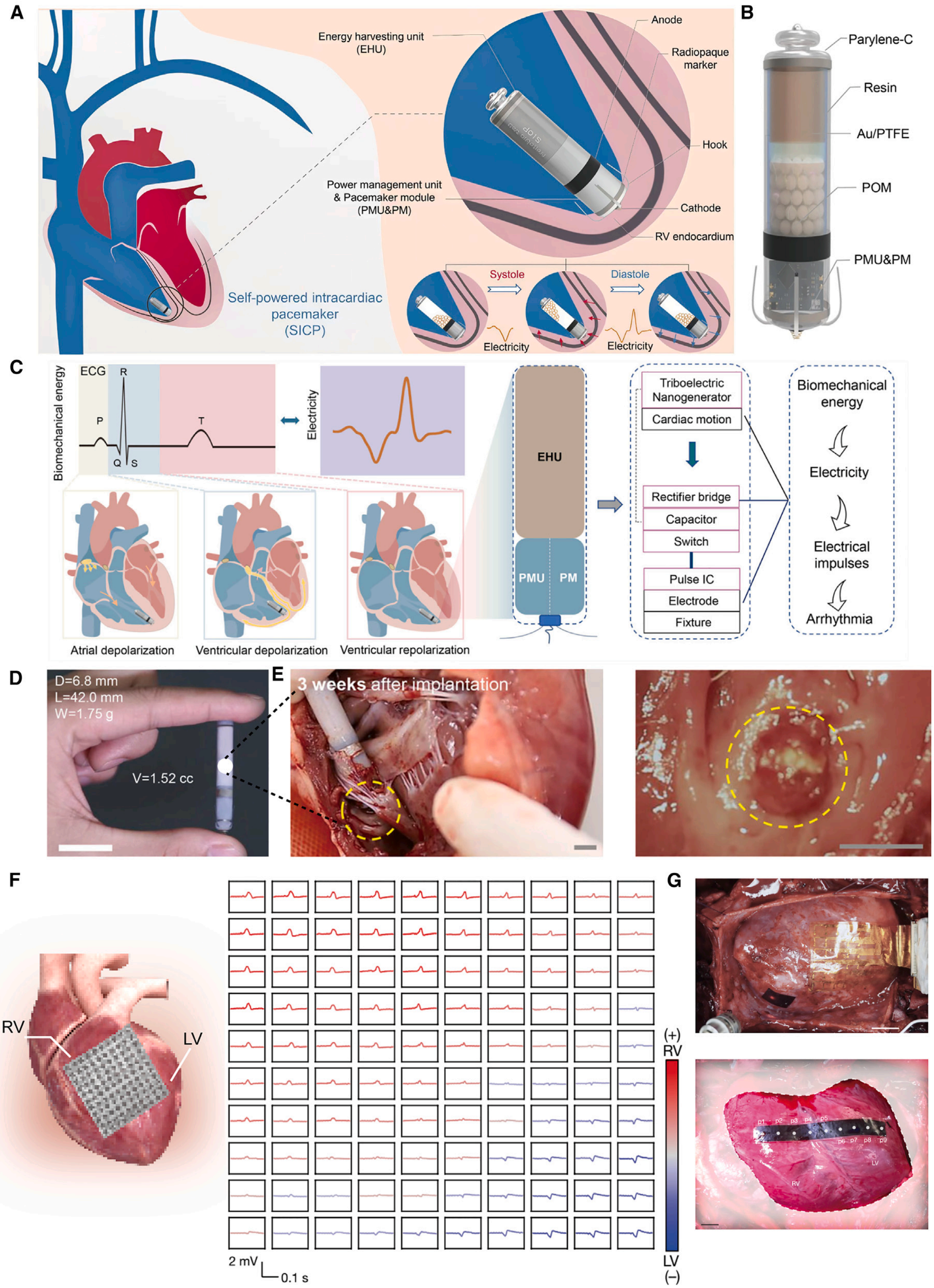


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(at 650 nm) could control the heart rate in pigs, increasing it from a normal 101 up to 128 bpm. This approach, based on hydrogenated amorphous silicon-based radial p-i-n junction (a-Si:H RJ) technology, offers a flexible, battery-free, and biocompatible solution for cardiac pacing that shows promise for clinical use (Figure 3E). More recently, Ausra et al. created a wireless, battery-free platform that was introduced for multi-modal, multi-site, real-time stimulation, sensing, and computing.[42] This technology expands the capability of implantable cardiac devices, allowing them to operate on demand in free-roaming animal models. The platform uses a custom-made soft-film electro-optical array tailored to the heart's geometry, capable of deforming with the heartbeat while maintaining high precision in stimulation delivery (Figure 3F).

However, because photovoltaic devices rely on external light sources, the light absorption and scattering by human tissues limits the power supply. The power output of photovoltaic devices is affected by ambient light intensity and spectral distribution, which can jeopardize the stable operation of implantable devices.[20,42] The encapsulation materials for photovoltaic devices must possess good biocompatibility and optical transparency. Some photovoltaic materials may also degrade or age over time, increasing the risk of infection and immune rejection.

One challenge of implantable pacemakers is achieving synchronized contractions across different parts of the heart. Li et al. developed a device using light energy for cardiac stimulation to address this issue (Figure 3G).[43] However, rather than harvesting light energy for power generation, their approach utilizes photostimulation to modulate cardiac activity, offering an alternative strategy for pacing. Given its potential impact, we provide a brief introduction here, while more detailed discussions can be found in the subsequent sections.

## Chemical and hydrodynamic energy in biological fluids

The human body contains abundant chemical energy for cellular function. For example, plasma is rich in dissolved glucose and can provide a constant energy source for implantable devices. Biofuel cells generate electricity from biochemical reactions in biological fluids. The process involves oxidation reactions at the anode (e.g., glucose oxidation) and corresponding redox reactions at the cathode. When the anode and cathode are connected through an external circuit, electrons flow between them, generating an electric current (Figure 1F).[44]

In 2019, Haeberlin et al. reported an energy harvester for endocardial implantation that uses intracardiac blood flow to drive a turbine rotor. This rotor was coupled magnetically to a sealed microgenerator, converting the turbine's mechanical energy into electrical power for a pacemaker.[45] In both simulation and *in vivo* experiments, this device, equipped with two 14-mm-diameter turbine rotors, produced an average power output of 10.2 ± 4.8 μW on the bench. By optimizing parameters such as stroke volume, heart rate, or turbine size, the output power could exceed 80 μW, with a power density of 237.1 $\mu W/cm^3$, surpassing the requirements of modern leadless pacemaker circuits. Wang et al. developed a high-power implantable biofuel cell (BFC) capable of converting chemical energy from biomass, such as glucose, into electrical energy.[46] This BFC utilized porous antifouling interfaces to enhance enzyme immobilization and antifouling properties. By coating carbon nanotube fibers with enzyme-containing polyvinyl alcohol and a polyvinyl alcohol-N-methyl-4(4′-formaldehyde styrene) pyridinium methanesulfonate precursor solution, followed by UV curing to form a 3D porous structure, the cell can maintain its performance for at least 45 days after implantation. It achieved a peak power output of 76.6 $mW/cm^3$.

Although the use of biological fluids to directly generate power for pacemakers is promising, several challenges remain. Long-term reliability is affected by the durability of enzymes and other components as well as issues like electrode degradation and biofouling. Enzyme catalytic efficiency and stability are sensitive to pH, temperature, and oxygen concentration in the physiological environment. The power output of BFCs depends on substrate concentrations in body fluids, which can fluctuate due to variations in health conditions and diet. The catalytic efficiency of BFCs also tends to decrease as enzyme activity declines, posing a risk of performance degradation during long-term use. Additionally, the lack of mechanical compatibility between bioelectrodes and tissues may cause inflammation or tissue damage.[47]

## External wireless energy source

Although wireless power sources still require batteries for driving the pacemakers externally, they still offer advantages over traditional battery-powered pacemakers, as they eliminate the need for battery replacement surgeries. The use of external wireless power sources also eliminates the risks of harmful material leakage from implanted batteries.[48] This reduces the biocompatibility requirements for patients, further enhancing the safety and reliability of the device.

**Figure 4. Latest research on battery-free leadless pacemakers**

(A) Based on the coupling effect of triboelectrification and electrostatic induction, a capsule-shaped pacemaker without wires in the heart cavity is developed.[24]

(B) Internal perspective structure of the device.[24]

(C) The device integrates an energy harvesting unit (EHU), a power management unit, and a pacemaker module to achieve pacing for atrioventricular block disease model animals.[24]

(D) Photograph of the SICP with a weight of 1.75 g and volume of 1.52 cc (diameter, 6.8 mm; length, 42 mm) (scale bar: 2 cm).[24]

(E) Photographs of the SICP fixed to the endocardium at 3 weeks (scale bar: 0.5 cm).[24]

(F) *In vitro* cardiac light stimulation experiments in rats. Por-Si devices can achieve high spatiotemporal multipoint pacing. The differences in QRS waveforms between the upper right and lower left regions reflect the distinct electrical activation patterns induced by photostimulation at different ventricular sites. Stimulation in the right ventricle (RV) results in narrower QRS complexes, indicating rapid and synchronized activation, while stimulation in the left ventricle (LV) leads to wider QRS complexes, suggesting delayed and dyssynchronous activation. This demonstrates the controlled cardiac activation sequences through targeted photostimulation.[43]

(G) *In vivo* light stimulation experiment of a pig heart. Precise control of ventricular pacing was realized by placing a Por-Si device on the right ventricular epicardial wall.[43]

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Ultrasound power transfer can drive a pacemaker by using an external ultrasound generator to emit an ultrasound beam to the implanted receiver that can convert the ultrasound into electrical impulses. In 2013, Jiang et al. developed a flexible piezoelectric ultrasonic energy harvester (PUEH) array to address the limitations of conventional rigid ultrasonic energy harvesters.[49] The PUEH utilized a 7 × 7 array of PZT/epoxy 1-3 piezoelectric composites as active elements, connected by multilayer flexible electrodes and encapsulated in an elastomer film. This structure allowed continuous voltage and current generation on both flat and curved surfaces when driven by ultrasound, with output signals exceeding 2 Voltage $_{\text{Peak-to-Peak}}$ (Vpp) and 4 μA, respectively. In 2021, Jin et al. developed an acoustic-electric communication device (AECD), enabling wireless energy delivery and data transmission based on ultrasound synchronization.[50] *In vivo* cardiac pacing experiments showed that the AECD received ultrasound energy and monitored the heart's rhythm using a built-in polyvinylidene fluoride (PVDF) sensor. The system detected abnormal heartbeats and delivered electrical stimulation, providing therapy for cardiac resynchronization (Figure 3H). The experiments demonstrated that the AECD accurately distinguished between normal and abnormal heartbeats and provided customizable electrical stimulation in response to abnormalities.

RF can also transmit energy wirelessly from the outside through electromagnetic fields to power the device. The RF receiver would capture electromagnetic waves generated by oscillating circuits outside the body. These high-frequency signals are fed to a receiving coil, which converts them into DC through a rectifier circuit (Figure 1G).[24,51] RF energy harvesting offers a wireless solution for powering implanted devices, reducing reliance on traditional battery systems.

In 2021, Choi et al. developed and tested *in vivo* a degradable pacemaker capable of degrading within a few months without requiring surgical removal.[12] The pacemaker operates wirelessly through inductive coupling between an external transmitter coil and an implanted receiver coil, eliminating the need for batteries and percutaneous leads. The pacemaker, measuring only 16 mm in length and width, 250 microns in thickness, and weighing 0.3 g, can be attached directly to the epicardium. The device demonstrated the ability to capture and regulate heart rhythms across various species and platforms, including human heart slices and the hearts of mice, rats, rabbits, and dogs. *In vivo* trials in a canine model confirmed its suitability for adult patients, while complete disintegration of the pacemaker was observed within three months of implantation in rats (Figure 3I). This approach addresses limitations of traditional temporary pacing devices and establishes a foundation for bioresorbable electronics.

In the following years, Wang et al. introduced a biocompatible wireless microelectronics system with a self-assembling design forming a lightweight microtubule pacemaker for intravascular implantation and pacing.[52] Energy was delivered wirelessly to the microtubule pacemaker using RF, providing electrical stimulation for cardiac electrotherapy (Figure 3J). In an anesthetized pig model, ECG rhythms showed consistent pacing spikes with QRS complexes (involving the Q, R, and S waves of the heart's electrical activity) and repolarized T waves, indicating cardiac stimulation at 60 bpm. The pacemaker proved effective for restoring cardiac contractions and performed overdrive pacing to enhance circulation. This self-assembled microtubule pacemaker offers a novel approach for intravascular pacemaker deployment and has potential applications for stimulating other organs, such as the stomach, nerves, and urinary system.

However, energy transmission using RF has practical challenges similar to those associated with ultrasound transmission. RF energy transmission is limited by the distance and alignment between devices. The absorption and scattering effects of human tissues reduce transmission efficiency, and patient movement or device misalignment may lead to insufficient power supply. High-frequency RF signals may cause local tissue temperature to rise, leading to tissue damage or immune responses. Prolonged exposure to RF fields may interfere with cardiac electrical signal conduction, increasing the risk of arrhythmias, especially for patients with existing electrophysiological disorders. The device design must balance energy efficiency with the biological load at the implantation site to avoid applying additional mechanical pressure on the myocardium and blood vessels.[53,54]

## FUTURE DIRECTIONS AND CHALLENGES

### Integration and miniaturization

In the field of implantable medical devices, the volume, flexibility, conformity, and biocompatibility are among the most basic requirements.[6] These devices should incorporate components for energy harvesting, power management, and pacing functions. Such an integrated system design can achieve the desired functionality in a self-contained environment without impairing the normal functions of human tissue. This requires the development of miniature, low-power pacing chips with energy storage and electrical pulse transmission capabilities as well as cardiac fixation devices and interventional delivery systems. Research efforts have been introduced to promote the miniaturization and integration of cardiac pacemakers. For example, Liu et al. designed a self-powered capsule-shaped pacemaker based on triboelectrification and electrostatic induction, utilizing contact electrification between polyoxymethylene particles and polytetrafluoroethylene films. Driven by cardiac motion, the device generates an open-circuit voltage of approximately 6.0 V and a short-circuit current of 0.2 μA, meeting the energy demands of the pacemaker. Furthermore, the application of a Parylene-C nanocoating on the device surface enhances biocompatibility and waterproof properties while also improving its long-term stability.[24] In terms of optoelectronic integration design, Li et al. developed a monolithic silicon photoelectrochemical platform that integrates a photodiode array with a cardiac stimulation module, achieving photoelectric conversion through the use of porous silicon materials. (Figure 4F) Specifically, the porous structure increases the surface area and reduces the recombination rate of photogenerated carriers, enhancing current generation efficiency. Simultaneously, this design minimizes device size, reducing its volume by two orders of magnitude compared to traditional devices. Moreover, it demonstrated pacing performance in a porcine heart model.[43] (Figure 4G).

In addition, the diversity of energy harvesting and transmission strategies has further advanced the miniaturization and integration of devices. Liu et al.'s triboelectric system continuously

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harvests mechanical energy during cardiac motion, achieving a self-powered closed-loop pacing function. Meanwhile, Li et al.'s optoelectronic system employs remote power delivery via an external light source, reducing device size while ensuring stable operation under varying physiological conditions.

To further miniaturize devices, several potential directions should be considered, such as optimizing materials and structural designs to reduce device volume, employing surface modification techniques to enhance precision and functionality, and innovating energy harvesting technologies. A focus on functional integration, material optimization, and diversified energy strategies will provide greater opportunities for the development of self-powered cardiac pacemakers.

## Material design for energy harvesting

In implantable energy harvesting systems, the choice of materials not only determines energy conversion efficiency but also directly impacts the stability, biocompatibility, and feasibility of long-term applications. Researchers have explored materials and structures that achieve high energy conversion rates while meeting the stringent environmental requirements of implantable devices. Material selection typically involves balancing several key factors: energy conversion efficiency, biodegradability, flexibility, stability, and durability in complex physiological environments. Commonly used materials include titanium metal casings, silicone, polyurethane, and epoxy resin as insulating materials and electrodes made of carbon and alloys. However, these materials may trigger immune responses, leading to localized inflammation and infection risks.

Quan et al. developed a polyvinyl alcohol (PVA) aerogel-based TENG incorporating β-lactoglobulin fibers, breaking the trade-off between material performance and output efficiency. The device features high toughness, biodegradability, and stable output performance. By introducing β-lactoglobulin fibers into PVA, which has low mechanical strength and water resistance, the study enhanced the material's strength and flexibility while preventing performance degradation due to bodily fluid infiltration after implantation. This approach exemplifies the balance between flexibility and mechanical strength while ensuring stable energy output during biodegradation.[55]

Structural design can integrate traditional materials for efficient energy harvesting. Dong et al. proposed a spiral piezoelectric energy harvester using porous poly vinylidene fluoride-co-trifluoroethylene (PVDF-TrFE) films. This design incorporates specific structural parameters such as film thickness, porosity optimized for strain amplification, and spiral radius tailored to fit pacemaker leads, all to ensure energy harvesting while maintaining flexibility and biocompatibility. This material strikes a balance between piezoelectric performance and flexibility. Although piezoelectric ceramics offer higher piezoelectric constants, their brittleness and rigidity make them unsuitable for dynamic physiological environments. PVDF-TrFE satisfies the dual requirements of flexibility and stability, and its porous structure enhances strain and energy conversion efficiency during bending. The spiral self-coiling design closely conforms to pacemaker leads, allowing it to harvest mechanical energy from cardiac motion without impairing heart function, thereby extending the pacemaker battery life by approximately 1.5 years[56]

Different energy harvesting approaches necessitate different material choices. Using thermoelectric materials, Zhang et al. designed a thermoelectric generation system combining a photothermal absorber and a radiative cooler. The system utilized a dielectric-metal stacked structure to optimize thermoelectric conversion efficiency. Traditional thermoelectric materials like $Bi_2Te_3$ perform well at high temperatures but exhibit limited efficiency at lower body temperatures. Zhang et al. employed multi-layered dielectric and metal combinations to maximize solar absorption while minimizing infrared thermal radiation loss, balancing energy capture and heat dissipation to ensure high conversion efficiency under varying environmental temperature gradients.[57]

Current energy-harvesting devices (e.g., TENGs or PENGs) are manufactured using multiple-step processes, and it is essential to explore simpler design and production methods for scalability. In the context of 3D printing, the use of multi-material properties has significantly enhanced the one-step fabrication process of custom energy-harvesting devices. Traditional manufacturing techniques often suffer from long processing times and limited availability of suitable raw materials, which hinder large-scale production. In contrast, 3D printing offers a more efficient and scalable alternative, enabling faster production with a wider range of materials. Hwang et al. fabricated a 3D TEG using direct inkjet printing, with carbon nanotubes (CNTs) as the core material. Leveraging CNTs' flexibility and conductivity, complex 3D structures were realized through inkjet printing. This approach offers performance tunability and microstructural customizability for energy-harvesting device fabrication.[58]

These studies highlight that material selection should be based on comprehensive considerations rather than maximizing a single performance attribute. A balanced strategy addressing energy harvesting efficiency, biocompatibility, and long-term stability will continue to guide the future development of energy-harvesting technologies.

## Safety concerns and evaluation

Long-term reliability plays a critical role in the design and application of implantable cardiac pacemakers, directly impacting the overall effectiveness of the device and the safety of the treatment process. Despite the relatively long battery life (5–10 years) of modern-day pacemakers, researchers are looking to self-powered options for developing next-generation implantable devices.

For implantable cardiac pacemakers, the evaluation of inflammatory responses to implanted materials *in vivo* is critically important. Studies have demonstrated that surface coatings and material selection play a pivotal role in reducing the risk of inflammation. For instance, porous silicon (Por-Si) materials exhibit minimal tissue inflammation post implantation, primarily due to optimized surface treatment techniques and passivation layers, such as oxide coatings, which suppress cytokine levels and the release of inflammatory mediators.[43] Magnesium-based or polymer coatings release degradation products without triggering immune cell activation, thereby ensuring the stability of surrounding tissues.[59] Evaluations of hemocompatibility and tissue inflammation further reveal that the use of optimized parylene coatings reduces platelet aggregation and coagulation responses. Histological analyses have also indicated the absence of fibrosis and inflammatory reactions at the implantation site.[54]

The pacemakers can also be paired with control systems that provide real-time feedback to allow doctors and patients to anticipate and detect abnormal cardiac conditions. There are also other clinical concerns, such as the compatibility between cardiac pacemakers and other medical instruments. For example, if a pacemaker were to malfunction, shift position, or fail in the high-intensity magnetic field of an MRI environment, then it could compromise imaging quality and pose safety risks to the patient. Optimizing the internal circuit design of the pacemaker and selecting low-magnetic-sensitivity materials can improve the device's MRI compatibility.

Most current research on battery-free implantable pacemakers remains at the stage of animal models. Transitioning to clinical trials requires strict adherence to regulatory standards, where quality control of medical devices is paramount. From the outset of designing battery-free pacemakers, rigorous validation based on scientific standards is necessary to ensure compatibility with the complex human environment. In clinical trials, protocols must be followed for implantation procedures, postoperative observation, and data recording, with all steps subject to strict oversight by regulatory agencies. Patients must be fully informed of the device's operating principles, risks, and benefits.

For data management, strict protocols must be adopted to protect patient privacy. All research must adhere to ethical guidelines and undergo thorough review by an ethics committee. Ethics committees, composed of professionals from diverse fields, review various aspects of the study, including its objectives, methods, and measures to protect patient rights.

## CONCLUSION

By utilizing biomechanical energy from heartbeats, body heat, biochemical reactions and ambient light, and ultrasound and electromagnetic waves, battery-free pacemakers have moved closer to achieving self-sustainability and reducing dependence on traditional power systems. The advancement of battery-free technologies also drives the miniaturization and system integration of these devices. However, several critical challenges still need to be addressed. The further improvement of energy conversion efficiency and the biocompatibility of materials is crucial to prevent potential adverse reactions, such as immune responses and inflammation, which can arise after implantation. Additionally, ensuring the long-term stability and reliability of battery-free pacemakers remains a challenge, particularly when faced with the complex and dynamic physiological conditions within the human body. To achieve optimal performance, future research must focus on enhancing system integration, optimizing synergistic energy utilization, and advancing intelligent control systems. The integration of advanced monitoring capabilities into pacemakers is another promising direction. By enabling real-time health monitoring and remote control through wireless communication technologies, future pacemakers could maintain cardiac rhythm while also providing valuable data, allowing for timely interventions and personalized care. The continued maturation of these technologies is expected to revolutionize cardiac care, improving patient quality of life, reducing the frequency of surgical interventions, and lowering overall medical risks.

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## DECLARATION OF INTERESTS

The authors declare no competing interests.

## REFERENCES

1. Lown, B., and Kosowsky, B.D. (1970). Artificial Cardiac Pacemakers. N. Engl. J. Med. *283*, 971–977. https://doi.org/10.1056/NEJM197010292831806.
2. Zheng, Q., Tang, Q., Wang, Z.L., and Li, Z. (2021). Self-powered cardiovascular electronic devices and systems. Nat. Rev. Cardiol. *18*, 7–21. https://doi.org/10.1038/s41569-020-0426-4.
3. Yi, Z., Wu, D., Su, Y., Yang, B., Ma, Y., Li, N., Zhang, Y., Zhang, W., and Wang, Z. (2024). Battery-less cardiac pacing using biomechanical energy harvesting. Device *2*, 100471. https://doi.org/10.1016/j.device.2024.100471.
4. Dong, L., Closson, A.B., Jin, C., Nie, Y., Cabe, A., Escobedo, D., Huang, S., Trase, I., Xu, Z., Chen, Z., et al. (2020). Multifunctional Pacemaker Lead for Cardiac Energy Harvesting and Pressure Sensing. Adv. Healthc. Mater. *9*, e2000053. https://doi.org/10.1002/adhm.202000053.
5. Nozariasbmarz, A., Collins, H., Dsouza, K., Polash, M.H., Hosseini, M., Hyland, M., Liu, J., Malhotra, A., Ortiz, F.M., Mohaddes, F., et al. (2020). Review of wearable thermoelectric energy harvesting: From body temperature to electronic systems. Appl. Energy *258*, 114069. https://doi.org/10.1016/j.apenergy.2019.114069.
6. Zhao, J., Ghannam, R., Htet, K.O., Liu, Y., Law, M.k., Roy, V.A.L., Michel, B., Imran, M.A., and Heidari, H. (2020). Self-Powered Implantable Medical Devices: Photovoltaic Energy Harvesting Review. Adv. Healthc. Mater. *9*, 2000779. https://doi.org/10.1002/adhm.202000779.
7. Rao, Y., Xu, C., Voss, M., Ying, P., Reith, H., Nielsch, K., Bechtold, T., and Hohlfeld, D. (2023). Fabrication and Characterization of a Thermoelectric Generator with High Aspect Ratio Thermolegs for Electrically Active Implants. Adv. Mater. Technol. *9*, 2301157. https://doi.org/10.1002/admt.202301157.
8. Wang, Z.L., and Song, J. (2006). Piezoelectric nanogenerators based on zinc oxide nanowire arrays. Science *312*, 242–246. https://doi.org/10.1126/science.1124005.
9. Shi, B., Liu, Z., Zheng, Q., Meng, J., Ouyang, H., Zou, Y., Jiang, D., Qu, X., Yu, M., Zhao, L., et al. (2019). Body-Integrated Self-Powered System for Wearable and Implantable Applications. ACS Nano *13*, 6017–6024. https://doi.org/10.1021/acsnano.9b02233.
10. Zhang, Y., Zhou, L., Liu, C., Gao, X., Zhou, Z., Duan, S., Deng, Q., Song, L., Jiang, H., Yu, L., et al. (2022). Self-powered pacemaker based on all-in-one flexible piezoelectric nanogenerator. Nano Energy *99*, 107420. https://doi.org/10.1016/j.nanoen.2022.107420.
11. Ma, Z., Cao, X., and Wang, N. (2023). Biophysical Sensors Based on Triboelectric Nanogenerators. Biosensors *13*, 423. https://doi.org/10.3390/bios13040423.

12. Choi, Y.S., Yin, R.T., Pfenniger, A., Koo, J., Avila, R., Benjamin Lee, K., Chen, S.W., Lee, G., Li, G., Qiao, Y., et al. (2021). Fully implantable and bioresorbable cardiac pacemakers without leads or batteries. Nat. Biotechnol. *39*, 1228–1238. https://doi.org/10.1038/s41587-021-00948-x.

13. Yang, P., Hou, X., Gao, X., Peng, Y., Li, Q., Niu, Q., and Liu, Q. (2024). Recent Trends in Self-Powered Photoelectrochemical Sensors: From the Perspective of Signal Output. ACS Sens. *9*, 577–588. https://doi.org/10.1021/acssensors.3c02198.

14. Franzina, N., Zurbuchen, A., Zumbrunnen, A., Niederhauser, T., Reichlin, T., Burger, J., Haeberlin, A., and Haeberlin, A. (2020). A miniaturized endocardial electromagnetic energy harvester for leadless cardiac pacemakers. PLoS One *15*, e0239667. https://doi.org/10.1371/journal.pone.0239667.

15. Hwang, G.T., Park, H., Lee, J.H., Oh, S., Park, K.I., Byun, M., Park, H., Ahn, G., Jeong, C.K., No, K., et al. (2014). Self-Powered Cardiac Pacemaker Enabled by Flexible Single Crystalline PMN-PT Piezoelectric Energy Harvester. Adv. Mater. *26*, 4880–4887. https://doi.org/10.1002/adma.201400562.

16. Jiang, L., Shao, T., Yang, X., Xiong, J., Hu, Y., Wang, Z., Gu, H., and Wang, J. (2025). One-dimensional potassium sodium niobates (1D KNN): Performance optimization and application prospects. J. Materiomics *11*, 100992. https://doi.org/10.1016/j.jmat.2024.100992.

17. Kong, X., Yang, L., Meng, F., Zhang, T., Zhang, H., Lin, Y.-H., Huang, H., Zhang, S., Guo, J., and Nan, C.-W. (2025). High-entropy engineered BaTiO3-based ceramic capacitors with greatly enhanced high-temperature energy storage performance. Nat. Commun. *16*, 885. https://doi.org/10.1038/s41467-025-56195-0.

18. Li, N., Yi, Z., Ma, Y., Xie, F., Huang, Y., Tian, Y., Dong, X., Liu, Y., Shao, X., Li, Y., et al. (2019). Direct Powering a Real Cardiac Pacemaker by Natural Energy of a Heartbeat. ACS Nano *13*, 2822–2830. https://doi.org/10.1021/acsnano.8b08567.

19. Xie, F., Qian, X., Li, N., Cui, D., Zhang, H., and Xu, Z. (2021). An experimental study on a piezoelectric vibration energy harvester for self-powered cardiac pacemakers. Ann. Transl. Med. *9*, 880. https://doi.org/10.21037/atm-21-2073.

20. Xie, F., Qian, X., Li, N., Cui, D., Zhang, H., and Xu, Z. (2021). In vitro and in vivo studies on the biocompatibility of a self-powered pacemaker with a flexible buckling piezoelectric vibration energy harvester for rats. Ann. Transl. Med. *9*, 800. https://doi.org/10.21037/atm-21-1707.

21. Bowen, C.R., Taylor, J., LeBoulbar, E., Zabek, D., Chauhan, A., and Vaish, R. (2014). Pyroelectric materials and devices for energy harvesting applications. Energy Environ. Sci. *7*, 3836–3856. https://doi.org/10.1039/c4ee01759e.

22. Ryu, H., Park, H.M., Kim, M.K., Kim, B., Myoung, H.S., Kim, T.Y., Yoon, H.J., Kwak, S.S., Kim, J., Hwang, T.H., et al. (2021). Self-rechargeable cardiac pacemaker system with triboelectric nanogenerators. Nat. Commun. *12*, 4374. https://doi.org/10.1038/s41467-021-24417-w.

23. Zhou, L., Zhang, Y., Cao, G., Zhang, C., Zheng, C., Meng, G., Lai, Y., Zhou, Z., Liu, Z., Liu, Z., et al. (2023). Wireless Self-Powered Optogenetic System for Long-Term Cardiac Neuromodulation to Improve Post-MI Cardiac Remodeling and Malignant Arrhythmia. Adv. Sci. *10*, 2205551. https://doi.org/10.1002/advs.202205551.

24. Liu, Z., Hu, Y., Qu, X., Liu, Y., Cheng, S., Zhang, Z., Shan, Y., Luo, R., Weng, S., Li, H., et al. (2024). A self-powered intracardiac pacemaker in swine model. Nat. Commun. *15*, 507. https://doi.org/10.1038/s41467-023-44510-6.

25. Jordaens, L., Berghmans, L., Van Wassenhove, E., and Clement, D.L. (1989). Behavior of a respiratory driven pacemaker and direct respiratory measurements. Pacing Clin. Electrophysiol. *12*, 1600–1606. https://doi.org/10.1111/j.1540-8159.1989.tb01838.x.

26. Zheng, Q., Shi, B., Fan, F., Wang, X., Yan, L., Yuan, W., Wang, S., Liu, H., Li, Z., and Wang, Z.L. (2014). In vivo powering of pacemaker by breathing-driven implanted triboelectric nanogenerator. Adv. Mater. *26*, 5851–5856. https://doi.org/10.1002/adma.201402064.

27. Zhang, H., Zhang, X.-S., Cheng, X., Liu, Y., Han, M., Xue, X., Wang, S., Yang, F., SmithaA, S., Zhang, H., and Xu, Z. (2015). A flexible and implantable piezoelectric generator harvesting energy from the pulsation of ascending aorta: in vitro and in vivo studies. Nano Energy *12*, 296–304. https://doi.org/10.1016/J.NANOEN.2014.12.038.

28. Xu, J., Zhai, Y., Yang, Y., Zhang, R., and Zhang, H. (2020). An integrated low-power Binary-PAM based wireless telemetry circuit for implantable cardiac pacemakers. Microelectron. J. *99*, 104747. https://doi.org/10.1016/j.mejo.2020.104747.

29. Sharma, D., Kanaujia, B.K., Kaim, V., Mittra, R., Arya, R.K., and Matekovits, L. (2022). Design and implementation of compact dual-band conformal antenna for leadless cardiac pacemaker system. Sci. Rep. *12*, 3165. https://doi.org/10.1038/s41598-022-06904-2.

30. Zhang, D., Wang, Y., and Yang, Y. (2019). Design, Performance, and Application of Thermoelectric Nanogenerators. Small *15*, 1805241. https://doi.org/10.1002/smll.201805241.

31. Rao, Y., Bechtold, T., and Hohlfeld, D. (2022). Design optimization of a packaged thermoelectric generator for electrically active implants. Microelectron. Reliab. *139*, 114843. https://doi.org/10.1016/j.microrel.2022.114843.

32. Shwetha, M., and Lakshmi, S. (2024). Harmless Sustainable Energy Resource using TEG with MPPT Based DC-DC Converter for Power Gain in Implantable Medical Devices. Trans. Electr. Electron. Mater. *25*, 608–635. https://doi.org/10.1007/s42341-024-00539-y.

33. Yang, Y., Dong Xu, G., and Liu, J. (2014). A Prototype of an Implantable Thermoelectric Generator for Permanent Power Supply to Body Inside a Medical Device. J. Med. Device. *8*, 014507. https://doi.org/10.1115/1.4025619.

34. Tupe, S., Shaikh, T., Kashid, D., and Ghodake, D. (2021). Study on Development of Power Supply System for Medical Implants using Thermoelectric Energy Harvesting from Human Body. Int. J. Res. Eng. Appl. Manag. *4*, 396–403. https://doi.org/10.18231/2454-9150.2018.1478.

35. Zhang, W., Zhang, L., Gao, H., Yang, W., Wang, S., Xing, L., and Xue, X. (2018). Self-Powered Implantable Skin-Like Glucometer for Real-Time Detection of Blood Glucose Level In Vivo. Nano-Micro Lett. *10*, 32. https://doi.org/10.1007/s40820-017-0185-x.

36. Gao, W., Wang, Y., and Lai, F. (2022). Thermoelectric energy harvesting for personalized healthcare. Smart Med. *1*, e20220016. https://doi.org/10.1002/smmd.20220016.

37. Zheng, Q., Zhang, H., Shi, B., Xue, X., Liu, Z., Jin, Y., Ma, Y., Zou, Y., Wang, X., An, Z., et al. (2016). In Vivo Self-Powered Wireless Cardiac Monitoring via Implantable Triboelectric Nanogenerator. ACS Nano *10*, 6510–6518. https://doi.org/10.1021/acsnano.6b02693.

38. Moon, E., Blaauw, D., and Phillips, J.D. (2017). Subcutaneous Photovoltaic Infrared Energy Harvesting for Bio-implantable Devices. IEEE Trans. Electron Devices *64*, 2432–2437. https://doi.org/10.1109/ted.2017.2681694.

39. Huang, X., Zhang, L., Zhang, Z., Guo, S., Shang, H., Li, Y., and Liu, J. (2019). Wearable biofuel cells based on the classification of enzyme for high power outputs and lifetimes. Biosens. Bioelectron. *124–125*, 40–52. https://doi.org/10.1016/j.bios.2018.09.086.

40. Haeberlin, A., Zurbuchen, A., Walpen, S., Schaerer, J., Niederhauser, T., Huber, C., Tanner, H., Servatius, H., Seiler, J., Haeberlin, H., et al. (2015). The first batteryless, solar-powered cardiac pacemaker. Heart Rhythm *12*, 1317–1323. https://doi.org/10.1016/j.hrthm.2015.02.032.

41. Liu, Z., Wen, B., Cao, L., Zhang, S., Lei, Y., Zhao, G., Chen, L., Wang, J., Shi, Y., Xu, J., et al. (2020). Photoelectric Cardiac Pacing by Flexible and Degradable Amorphous Si Radial Junction Stimulators. Adv. Healthc. Mater. *9*, 1901342. https://doi.org/10.1002/adhm.201901342.

42. Ausra, J., Madrid, M., Yin, R.T., Hanna, J., Arnott, S., Brennan, J.A., Peralta, R., Clausen, D., Bakall, J.A., Efimov, I.R., and Gutruf, P. (2022). Wireless, fully implantable cardiac stimulation and recording with on-device

computation for closed-loop pacing and defibrillation. Sci. Adv. *8*, eabq7469. https://doi.org/10.1126/sciadv.abq7469.

43. Li, P., Zhang, J., Hayashi, H., Yue, J., Li, W., Yang, C., Sun, C., Shi, J., Huberman-Shlaes, J., Hibino, N., and Tian, B. (2024). Monolithic silicon for high spatiotemporal translational photostimulation. Nature *626*, 990–998. https://doi.org/10.1038/s41586-024-07016-9.

44. Dagdeviren, C., Li, Z., and Wang, Z.L. (2017). Energy Harvesting from the Animal/Human Body for Self-Powered Electronics. Annu. Rev. Biomed. Eng. *19*, 85–108. https://doi.org/10.1146/annurev-bioeng-071516-044517.

45. Haeberlin, A., Rosch, Y., Tholl, M.V., Gugler, Y., Okle, J., Heinisch, P.P., Reichlin, T., Burger, J., and Zurbuchen, A. (2020). Intracardiac Turbines Suitable for Catheter-Based Implantation—An Approach to Power Battery and Leadless Cardiac Pacemakers? IEEE. Trans. Biomed. Eng. *67*, 1159–1166. https://doi.org/10.1109/tbme.2019.2932028.

46. Wang, L., He, E., Gao, R., Wu, X., Zhou, A., Lu, J., Zhao, T., Li, J., Yun, Y., Li, L., et al. (2021). Designing Porous Antifouling Interfaces for High-Power Implantable Biofuel Cell. Adv. Funct. Mater. *31*, 2107160. https://doi.org/10.1002/adfm.202107160.

47. Guan, S., Wang, J., Yang, Y., Zhu, X., Zhou, J., Ye, D., Chen, R., Dai, H., and Liao, Q. (2023). Highly Stretchable and Flexible Electrospinning-Based Biofuel Cell for Implantable Electronic. Adv. Funct. Mater. *33*, 2303134. https://doi.org/10.1002/adfm.202303134.

48. Khan, S.R., Pavuluri, S.K., Cummins, G., and Desmulliez, M.P.Y. (2020). Wireless Power Transfer Techniques for Implantable Medical Devices: A Review. Sensors *20*, 3487. https://doi.org/10.3390/s20123487.

49. Jiang, L., Yang, Y., Chen, R., Lu, G., Li, R., Li, D., Humayun, M.S., Shung, K.K., Zhu, J., Chen, Y., and Zhou, Q. (2019). Flexible piezoelectric ultrasonic energy harvester array for bio-implantable wireless generator. Nano Energy *56*, 216–224. https://doi.org/10.1016/j.nanoen.2018.11.052.

50. Jin, P., Fu, J., Wang, F., Zhang, Y., Wang, P., Liu, X., Jiao, Y., Li, H., Chen, Y., Ma, Y., and Feng, X. (2021). A flexible, stretchable system for simultaneous acoustic energy transfer and communication. Sci. Adv. *7*, eabg2507. https://doi.org/10.1126/sciadv.abg2507.

51. Bose, P., Khaleghi, A., Mahmood, S., Albatat, M., Bergsland, J., and Balasingham, I. (2019). Evaluation of Data Telemetry for Future Leadless Cardiac Pacemaker. IEEE Access *7*, 157933–157945. https://doi.org/10.1109/access.2019.2950146.

52. Wang, S., Cui, Q., Abiri, P., Roustaei, M., Zhu, E., Li, Y.R., Wang, K., Duarte, S., Yang, L., Ebrahimi, R., et al. (2023). A self-assembled implantable microtubular pacemaker for wireless cardiac electrotherapy. Sci. Adv. *9*, eadj0540. https://doi.org/10.1126/sciadv.adj0540.

53. Kwon, K., Kim, J.U., Won, S.M., Zhao, J., Avila, R., Wang, H., Chun, K.S., Jang, H., Lee, K.H., Kim, J.-H., et al. (2023). A battery-less wireless implant for the continuous monitoring of vascular pressure, flow rate and temperature. Nat. Biomed. Eng. *7*, 1215–1228. https://doi.org/10.1038/s41551-023-01022-4.

54. Li, S., Lu, D., Li, S., Liu, J., Xu, Y., Yan, Y., Rodriguez, J.Z., Bai, H., Avila, R., Kang, S., et al. (2024). Bioresorbable, wireless, passive sensors for continuous pH measurements and early detection of gastric leakage. Sci. Adv. *10*, eadj0268. https://doi.org/10.1126/sciadv.adj0268.

55. Quan, Y., Wang, E., Ouyang, H., Xu, L., Jiang, L., Teng, L., Li, J., Luo, L., Wu, X., Zeng, Z., et al. (2024). Biodegradable and Implantable Triboelectric Nanogenerator Improved by β-Lactoglobulin Fibrils-Assisted Flexible PVA Porous Film. Adv. Sci. 2409914. https://doi.org/10.1002/advs.202409914.

56. Dong, L., Closson, A.B., Oglesby, M., Escobedo, D., Han, X., Nie, Y., Huang, S., Feldman, M.D., Chen, Z., and Zhang, J.X. (2019). In vivo cardiac power generation enabled by an integrated helical piezoelectric pacemaker lead. Nano Energy *66*, 104085. https://doi.org/10.1016/j.nanoen.2019.104085.

57. Zhang, S., Liu, Z., Wu, Z., Yao, Z., Zhang, W., Zhang, Y., Guan, Z., Lin, H., Cheng, H., Mu, E., et al. (2024). Boosting self-powered wearable thermoelectric generator with solar absorber and radiative cooler. Nano Energy *132*, 110381. https://doi.org/10.1016/j.nanoen.2024.110381.

58. Hwang, S., Jang, D., Lee, B., Ryu, Y.S., Kwak, J., Kim, H., and Chung, S. (2023). All Direct Ink Writing of 3D Compliant Carbon Thermoelectric Generators for High-Energy Conversion Efficiency. Adv. Energy Mater. *13*, 2204171. https://doi.org/10.1002/aenm.202204171.

59. Choi, Y.S., Jeong, H., Yin, R.T., Avila, R., Pfenniger, A., Yoo, J., Lee, J.Y., Tzavelis, A., Lee, Y.J., Chen, S.W., et al. (2022). A transient, closed-loop network of wireless, body-integrated devices for autonomous electrotherapy. Science *376*, 1006–1012. https://doi.org/10.1126/science.abm1703.

60. Liu, M., Qian, F., Mi, J., and Zuo, L. (2022). Biomechanical energy harvesting for wearable and mobile devices: State-of-the-art and future directions. Appl. Energy *321*, 119379. https://doi.org/10.1016/j.apenergy.2022.119379.

61. Amin Karami, M., and Inman, D.J. (2012). Powering pacemakers from heartbeat vibrations using linear and nonlinear energy harvesters. Appl. Phys. Lett. *100*, 042901. https://doi.org/10.1063/1.3679102.

62. Eppink, M.H.M., Ventura, S.P.M., Coutinho, J.A.P., and Wijffels, R.H. (2021). Multiproduct Microalgae Biorefineries Mediated by Ionic Liquids. Trends Biotechnol. *39*, 1131–1143. https://doi.org/10.1016/j.tibtech.2021.02.009.

63. Zhao, B., Qi, N., Zhang, K.-Q., and Gong, X. (2016). Fabrication of free-standing silk fibroin films containing Ag nanowires/NaYF4:Yb,Er nanocomposites with metal-enhanced fluorescence behavior. Phys. Chem. Chem. Phys. *18*, 15289–15294. https://doi.org/10.1039/c6cp02024k.

64. Xu, L., Xiong, Y., Mei, A., Hu, Y., Rong, Y., Zhou, Y., Hu, B., and Han, H. (2018). Efficient Perovskite Photovoltaic-Thermoelectric Hybrid Device. Adv. Energy Mater. *8*, 1702937. https://doi.org/10.1002/aenm.201702937.

65. Azimi, S., Golabchi, A., Nekookar, A., Rabbani, S., Amiri, M.H., Asadi, K., and Abolhasani, M.M. (2021). Self-powered cardiac pacemaker by piezoelectric polymer nanogenerator implant. Nano Energy *83*, 105781. https://doi.org/10.1016/j.nanoen.2021.105781.

66. DeForge, W.F. (2019). Cardiac pacemakers: a basic review of the history and current technology. J. Vet. Cardiol. *22*, 40–50. https://doi.org/10.1016/j.jvc.2019.01.001.

67. Ryu, H., Park, H.-m., Kim, M.-K., Kim, B., Myoung, H.S., Kim, T.Y., Yoon, H.-J., Kwak, S.S., Kim, J., Hwang, T.H., et al. (2021). Self-rechargeable cardiac pacemaker system with triboelectric nanogenerators. Nat. Commun. *12*, 4374. https://doi.org/10.1038/s41467-021-24417-w.

68. MacVittie, K., Halámek, J., Halámková, L., Southcott, M., Jemison, W.D., Lobel, R., Katz, E., and Science, E. (2013). From "cyborg" lobsters to a pacemaker powered by implantable biofuel cells. Energy Environ. Sci. *6*, 81–86. https://doi.org/10.1039/C2EE23209J.

69. Imani, I.M., Kim, H.S., Shin, J., Lee, D.G., Park, J., Vaidya, A., Kim, C., Baik, J.M., Zhang, Y.S., Kang, H., et al. (2024). Advanced Ultrasound Energy Transfer Technologies using Metamaterial Structures. Adv. Sci. *11*, e2401494. https://doi.org/10.1002/advs.202401494.

70. McArdle, W.D., Katch, F.I., and Katch, V.L. (2010). Exercise Physiology: Nutrition, Energy, and Human Performance (Lippincott Williams & Wilkins).

71. Villà-Freixa, J. (2004). Book Review: Thermodynamics of Biochemical Reactions. By Robert A. Alberty. ChemPhysChem *5*, 287–288. https://doi.org/10.1002/cphc.200490010.

72. Baker, L.B. (2019). Physiology of sweat gland function: The roles of sweating and sweat composition in human health. Temperature *6*, 211–259. https://doi.org/10.1080/23328940.2019.1632145.

73. Southcott, M., MacVittie, K., Halámek, J., Halámková, L., Jemison, W.D., Lobel, R., and Katz, E. (2013). A pacemaker powered by an implantable biofuel cell operating under conditions mimicking the human blood circulatory system – battery not included. Phys. Chem. Chem. Phys. *15*, 6278–6283. https://doi.org/10.1039/c3cp50929j.

74. Dagdeviren, C., Yang, B.D., Su, Y., Tran, P.L., Joe, P., Anderson, E., Xia, J., Doraiswamy, V., Dehdashti, B., Feng, X., et al. (2014). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and

diaphragm. Proc. Natl. Acad. Sci. USA *111*, 1927–1932. https://doi.org/10.1073/pnas.1317233111.

75. Zheng, Q., Shi, B., Fan, F., Wang, X., Yan, L., Yuan, W., Wang, S., Liu, H., Li, Z., and Wang, Z.L. (2014). In Vivo Powering of Pacemaker by Breathing-Driven Implanted Triboelectric Nanogenerator. Adv. Mater. *26*, 5851–5856. https://doi.org/10.1002/adma.201402064.

76. Ouyang, H., Liu, Z., Li, N., Shi, B., Zou, Y., Xie, F., Ma, Y., Li, Z., Li, H., Zheng, Q., et al. (2019). Symbiotic cardiac pacemaker. Nat. Commun. *10*, 1821. https://doi.org/10.1038/s41467-019-09851-1.

77. Yang, S.-K., Chen, C.-H., Zhu, Y.-J., and Chen, K.-J. (2024). Remote Charging for Cardiac Pacemakers Using Transcutaneous Optical Energy Transmission System. Sens. Mater. *36*, 3335. https://doi.org/10.18494/sam5039.